Radiation Dose to the Fetus From Computed Tomography of Pregnant Patients-Development and Validation of a Web-Based Tool

Saltybaeva, Natalia ; Platon, Alexandra ; Poletti, Pierre-Alexandre ; Hinzpeter, Ricarda ; Merce, Marta Sans ; Alkadhi, Hatem

Abstract: OBJECTIVE Estimations of radiation dose absorbed by the fetus from computed tomography (CT) in pregnant patients is mandatory, but currently available methods are not feasible in clinical routine. The aims of this study were to develop and validate a tool for assessment of fetal dose from CT of pregnant patients and to develop a user-friendly web interface for fast fetal dose calculations. METHODS In the first study part, 750 Monte Carlo (MC) simulations were performed on phantoms representing pregnant patients at various gestational stages. The MC code simulating vendor-independent dose distributions was validated against CT dose index (CTDI) measurements performed on CT scanners of 2 vendors. The volume CTDI-normalized fetal dose values from MC simulations were used for developing the computational algorithm enabling fetal dose assessments from CT of various body regions at different exposure settings. In the institutional review board-approved second part, the algorithm was validated against patient-specific MC simulations performed on CT data of 29 pregnant patients (gestational ages 8-35 weeks) who underwent CT. Furthermore, the tool was compared with a commercially available software. A user-friendly web-based interface for fetal dose calculations was created. RESULTS Weighted CTDI values obtained from MC simulations were in excellent agreement with measurements performed on the 2 CT systems (average error, 4%). The median fetal dose from abdominal CT in pregnant patients was 2.7 mGy, showing moderate correlation with maternal perimeter (r = 0.69). The algorithm provided accurate estimates of fetal doses (average error, 11%), being more accurate than the commercially available tool. The web-based interface (www.fetaldose.org) enabling vendor-independent calculations of fetal doses from CT requires the input of gestational age, volume CTDI, tube voltage, and scan region. CONCLUSIONS A tool for fetal dose assessments from CT of pregnant patients was developed and validated being freely available on a user-friendly web interface.

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Radiation Dose to the Fetus From Computed Tomography of Pregnant Patients—Development and Validation of a Web-Based Tool

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Objective: Estimations of radiation dose absorbed by the fetus from computed tomography (CT) in pregnant patients is mandatory, but currently available methods are not feasible in clinical routine. The aims of this study were to develop and validate a tool for assessment of fetal dose from CT of pregnant patients and to develop a user-friendly web interface for fast fetal dose calculations.

Methods: In the first study part, 750 Monte Carlo (MC) simulations were performed on phantoms representing pregnant patients at various gestational stages. The MC code simulating vendor-independent dose distributions was validated against CT dose index (CTDI) measurements performed on CT scanners of 2 vendors. The volume CTDI–normalized fetal dose values from MC simulations were used for developing the computational algorithm enabling fetal dose assessments from CT of various body regions at different exposure settings. In the institutional review board–approved second part, the algorithm was validated against patient-specific MC simulations performed on CT data of 29 pregnant patients (gestational ages 8–35 weeks) who underwent CT. Furthermore, the tool was compared with a commercially available software. A user-friendly web-based interface for fetal dose calculations was created.

Results: Weighted CTDI values obtained from MC simulations were in excellent agreement with measurements performed on the 2 CT systems (average error, 4%). The median fetal dose from abdominal CT in pregnant patients was 2.7 mGy, showing moderate correlation with maternal perimeter (r = 0.69). The algorithm provided accurate estimates of fetal doses (average error, 11%), being more accurate than the commercially available tool. The web-based interface (www.fetaldose.org) enabling vendor-independent calculations of fetal doses from CT requires the input of gestational age, volume CTDI, tube voltage, and scan region.

Conclusions: A tool for fetal dose assessments from CT of pregnant patients was developed and validated being freely available on a user-friendly web interface.

Key Words: computed tomography, pregnant, fetus, radiation dosage

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The number of computed tomography (CT) examinations increased over the past decade in the general population[1,2] and also in specific groups such as pregnant patients.[3–5] Because ionizing radiation has been associated with the development of cancer,[6,7] CT in pregnant patients requires careful consideration of the radiation-related risks to both the mother and fetus. Although the risk to the mother from ionizing radiation can be assessed by several methods,[6,8] knowledge about the risk of the fetus is limited and is associated with a wider range of uncertainty,[9,10] which is also related to difficulties in determining the fetal dose. Knowing the amount of ionizing radiation absorbed by the fetus, however, is relevant for estimating the risk regarding both embryogenesis and carcinogenesis.[11,12]

The radiation dose absorbed by the fetus depends on many factors, including patient anatomy, gestational age, proximity of the uterus to the scanned body region, and technical parameters of the respective CT examination.[13] Although fetal doses from CT of the mothers' neck or head are considered negligible owing to the distance between the examined region and the uterus,[14] CT examinations including the uterus in the primary irradiated field may yield fetal doses of up to 50 mGy and beyond.[15,16] Because of the radiosensitivity of the fetus, multiple national and international advisory bodies, including the American College of Radiology, the International Atomic Energy Agency, and the International Commission on Radiological Protection, published recommendations and guidelines for imaging pregnant patients with ionizing radiation.[17–19] According to these, calculations and recording of the radiation dose received by the fetus from radiological examinations are recommended.

The exact assessment of fetal radiation dose constitutes a considerable challenge because the energy deposition cannot be directly measured in patients for ethical and technical reasons. An alternative approach using anthropomorphic phantoms as substitute has been considered by several groups.[10,20,21] For this, direct dose measurements in the phantom's uterus were performed using thermoluminescent dosimeters, later replaced by optically stimulated luminescence and metal oxide semiconductor field-effect transistor dosimeters. However, such methods are not practical for routine clinical use.

A more recent approach, investigated by several groups,[22–24] was based on Monte Carlo (MC) simulations using patient-specific models. The MC method is currently considered standard for dose assessments in diagnostic imaging.[25] However, this method can hardly be implemented in clinical routine because of its complexity. In addition, this approach is not applicable when the fetus is included only partially or located outside of the scan range, for example in CT pulmonary angiography.

To overcome these limitations, some commercially available tools utilizing the data from prerun MC simulations on virtual phantoms such as ImPACT[26] or CT-Expo[15] were developed. However, most of these existing tools are based on simplified computational phantoms and are associated with relatively large errors in dose assessments when compared with realistic anatomy.[27–29] More advanced tools such as the NCICT software[30] are based on more realistic human anatomy but do not include pregnant models. Recently developed tools such as DukeSim[31] and VirtualDose[32] improved the accuracy of patient modeling; however, results of these tools were not validated against dose

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measurements or detailed patient-specific calculations. In addition, such software packages are costly, rarely available outside of larger radiological departments, and require skilled staff to be used.

The purposes of this study were to develop and validate an algorithm for accurate assessment of fetal dose from the CT of pregnant patients of any body region and to develop a user-friendly web-based interface for fast fetal dose calculations.

METHODS

Computational Algorithm

Details about the CT source modeling and validation of the source modeling can be found in the Supplementary material, http://links.lww.com/RLI/A537.

Fetal Dose Calculations

To calculate fetal dose, we used hybrid phantoms representing pregnant patients at the end of the third, sixth, and ninth months of pregnancy developed by Xu et al[33] (Rensselaer Polytechnic Institute, RPI, New York, NY). In contrast to stylized models, hybrid computational phantoms represent realistic geometries of pregnant patients.[34,35] These phantoms were voxelized to a resolution of $3 \times 3 \times 3$ mm^3 and the arms of the phantoms were removed, since patients' arms are usually located outside of the field of view (FoV).

These phantoms were used as an input volume for the simulation tool described above. For each of the phantoms, 47 axial scans with 15-mm width in the cranial direction were simulated to obtain the radiation dose distribution covering the body region from the upper chest to the lower pelvis (total coverage 47×15 mm) (Fig. 1). Further details regarding fetal dose calculations can be found in the Supplementary material, http://links.lww.com/RLI/A537.

Validation and Comparison

We validated the computational algorithm using CT dose index (CTDI)–normalized values obtained from the computational phantom against the results from MC simulations performed on patient data. For this, we included 29 pregnant women (mean age, 31 ± 6 years; age range, 20–42 years; gestational ages, 8–35 weeks) who underwent clinically indicated CT. The data were acquired from 2 different hospitals to ensure variations of CT protocols and CT scanners. This retrospective study part was approved by institutional review boards and local ethics committees of both study sites; written informed consent requirement was waived.

The indications for CT in these patients were polytrauma (n = 10) and acute abdomen (n = 19). The patients with polytrauma underwent whole-body CT (including the abdomen), whereas the patients with acute abdomen underwent abdominal CT only. Of the 29 patients, 14 (48%) underwent CT on a 128-slice CT scanner (SOMATOM Flash, Siemens Healthineers, Forchheim, Germany) and 15 patients (52%) on a 64-slice CT scanner (Discovery CT750 HD, GE Healthcare, Waukesha, WI) (Table 1). The patients' CT images were used as input volume for patient-specific MC simulations. The simulations were applied to patient-specific computational models using the tube voltage, collimation, gantry rotation time, and pitch from the respective CT acquisition. For patients scanned with automatic exposure control, the tube current modulation (TCM) curves were extracted from the DICOM headers and were used as input data for MC simulations. The effect of angular tube position at the beginning of the scan on dose distribution was minimized by repeating each simulation 4 times with start angles of 0, 90, 180, and 270 degrees, respectively. Further details regarding fetal dose calculations can be found in the Supplementary material, http://links.lww.com/RLI/A537.

Web-Based Software Tool

The final aim of the study was to integrate our computational approach into a user-friendly, web-based interface and to create a tool that can be easily used by medical professionals in their clinical routine. The tool was designed on a web-based platform with intuitive graphical user interface. The platform is compatible with various web browsers, including Google Chrome, Mozilla Firefox, and Microsoft Internet Explorer, and can be accessed also from mobile devices using iOS and Android operating systems. The main interface consists of a parameter

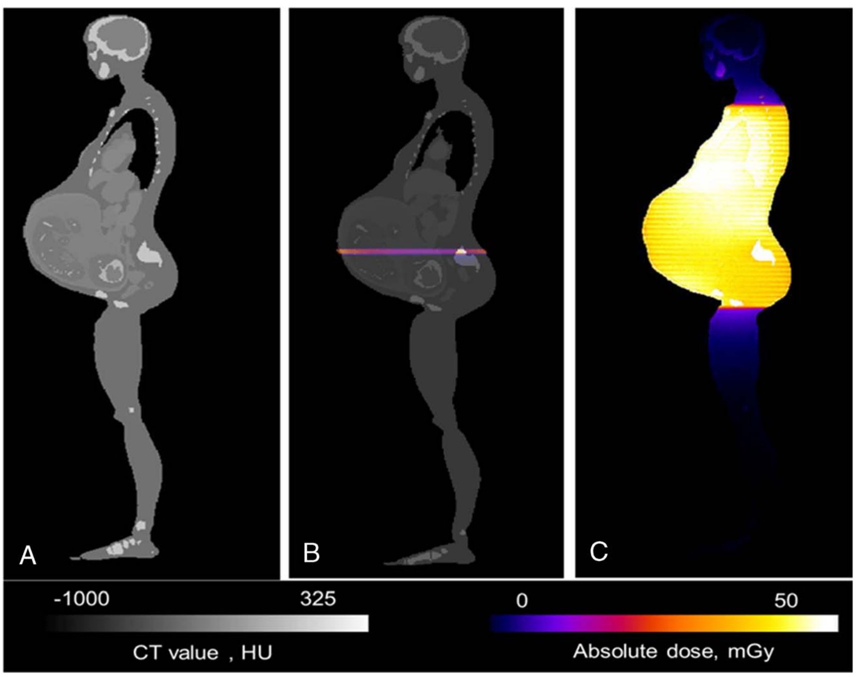

FIGURE 1. Example of the voxelized Rensselaer Polytechnic Institute phantom simulating a pregnant woman at the end of the ninth month (A), the dose distribution from a single 15-mm slice (B), and dose distributions of a chest-abdomen CT (C).

TABLE 1. Summary of the CT Protocol Parameters

Parameter	128-Slice CT (Siemens)	64-Slice CT (GE)
Tube voltage, kV	100, 120	120
Total collimation width, mm	19.2, 38.4	40
Rotation time, s	0.5	0.7
Pitch	0.4, 0.6, 0.95, 1.4	1.375
Automatic exposure control	On, off	Off

Abbreviations: CT, computed tomography, kV, kilovolts.

selection panel, a scan range display, and a result display. The following input parameters are required: gestational age (in trimester), tube voltage, and volume CTDI ($CTDI_{vol}$). Optional parameters are maternal perimeter and patient ID.

Statistical Analysis

The data are provided as frequency and percentage, mean value and standard deviation, or median with interquartile ranges, as appropriate. Normality of the data was tested using the Shapiro-Wilk test. Pearson correlation analysis was performed to determine the relationship between fetal dose and maternal size, between the relative error of dose provided by the computational algorithm to patient-specific MC simulations and maternal size, and between relative error and gestational age. The linear regression function obtained from Pearson analysis was used to increase the accuracy of fetal dose calculations by taking maternal perimeter into account. All statistical analyses were performed using commercially available software (SPSS, release 24.0; SPSS, Chicago, IL). A 2-tailed P value below 0.5 was considered to indicate statistical significance.

RESULTS

Accuracy of MC Simulations

The differences between measured and simulated center CTDI, periphery CTDI, and weighted CTDI values are shown in Table 2. The maximum difference for weighted CTDI was 6% at 100 kV, whereas the average difference between measurements and simulations was 4.6%.

Phantom-Based Fetal Dose Values

The dose values obtained by MC simulations performed on the RPI phantoms and tabulated as a function of 15-mm axial scans for 5 tube voltages and 3 gestational ages are shown in Supplementary Table 1, http://links.lww.com/RLI/A537.

Validation of the Tool

The absolute dose values calculated from patient specific MC simulations and those calculated by our tool are shown in Table 3. The median fetal dose calculated from patient-specific MC simulations was 2.7 mGy (interquartile range, 10.6 mGy). The fetal dose normalized by the $CTDI_{vol}$ showed a significant, moderate correlation with maternal perimeter ($r = 0.63$, $P < 0.01$) (Fig. 2). The relative difference between fetal doses from patient-specific MC simulations to those calculated by the computational algorithm (ΔD) was, on average, 18%. The largest discrepancies of 39% between patient-specific dose values and those calculated by the algorithm were found in polytrauma patients having the arms and external devices located within the scan-FoV. In these cases, the algorithm overestimated the dose received by fetus. The relative error between the results provided by the computational algorithm and the values from patient-specific MC simulations showed a significant correlation with maternal perimeter ($r = 0.69$, $P < 0.01$) (Fig. 3A). The correlation between the relative error of the proposed algorithm and the gestational age was not significant ($r = -0.12$, $P = 0.52$).

Because the radiation dose to the fetus correlated with patient size, we further improved our dose calculations by taking the maternal perimeter into account. For this, the fetal dose was corrected by maternal perimeter (D_{FD}^{cor}) as follows:

$$D_{FD}^{cor} = \frac{D_{FD}}{1-a \times P-b}, \qquad (1)$$

where D_{FD} is noncorrected fetal dose calculated by the algorithm, P is the maternal perimeter, and a and b are coefficient of linear interpolation defined from the Pearson correlation. With this correction, the average relative difference between the results provided by the computational algorithm and patient-specific MC simulations was reduced to 11% (Fig. 3B).

Comparison With Other Methods

The results of our computational algorithm were in good agreement with those from the commercially available software tool, with an average relative difference of 10%. Compared with the reference standard (ie, patient-specific MC simulations) our algorithm showed a closer agreement (relative error, 18% ± 11%) than the commercially available product (relative error, 20% ± 29%). The accuracy of our tool was further improved when the maternal perimeter was taken into account, resulting in a relative error to the reference standard of 11% ± 6%. A comparison of dose values obtained by our tool to those from others[22] is shown in Supplementary Table 2, http://links.lww.com/RLI/A537.

TABLE 2. Comparison of Measured and Simulated $CTDI_w$ Values From a Single Axial Scan in the CTDI Body Phantom

			CTDI Measured, mGy/100 mAs			CTDI Simulated, mGy/100 mAs			Relative Difference, %		
CT Scanner	Tube Voltage, kV	Total Collimation Width, mm	$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_c$	$CTDI_p$	$CTDI_w$	$CTDI_c$	$CTDI_p$	$CTDI_w$
128-slice CT	100	19.2	2.5	6	4.8	2.2	5.4	4.5	−12	−10	−6
		38.4	2.4	5.9	4.7	2.2	5.5	4.7	−8	−7	0
	120	19.2	4.5	10.1	8.2	4.0	9.8	7.9	−11	−3	−4
		38.4	4.4	9.7	7.9	4.0	9.8	7.9	−9	1	0
64-slice CT	120	40.0	4.3	9.3	7.6	4.1	9.9	8.0	−5	6	4

Abbreviations: CT, computed tomography; CTDI, CT dose index; $CTDI_c$, center CTDI; $CTDI_p$, periphery CTDI, $CTDI_w$, weighted CTDI.

TABLE 3. Comparison Between Fetal Doses Calculated by Patient-Specific MC Simulations and Values Calculated by Our Tool (www.fetaldose.org) With and Without Taking Maternal Perimeter Into Account

Patient Number	Gestation Weeks	$CTDI_{vol}$, mGy	Perimeter, mm	Patient-Specific Fetal Dose, mGy	Fetal Dose by fetaldose.org, mGy	Relative Error, %	Fetal Dose From www.fetaldose.org Taking Perimeter Into Account	Relative Error, %
1	35	11.83	1131	12.4	10.3	−17	11.0	−11
2	15	15.4	780	18.8	14.3	−24	21.1	12
3	8	14.13	1013	14.5	15.7	8	17.2	18
4	15	6.2	1000	7.5	5.8	−24	6.4	−15
5	11	4.6	981	5.5	5.1	−8	5.8	5
6	11	10.7	1000	15.6	12.5	−20	13.9	−11
7	26	14.3	898	17.9	13.3	−26	16.7	−7
8	32	10.1	1025	13.7	8.8	−36	11.0	−20
9	27	6.35	855	6.4	5.1	−19	6.8	7
10	9	7.2	900	8.4	8.0	−5	10.0	19
11	9	8.06	960	13.6	9.4	−31	11.0	−19
12	8	10.7	1023	12.9	11.9	−8	12.9	0
13	8	6.2	955	9.5	6.9	−28	8.0	−16
14	8	5.6	985	5.9	6.2	5	7.0	18
15	10	1.8	911	2.5	2.1	−16	2.6	4
16	11	1.8	872	2.7	2.1	−22	2.7	1
17	11	1.8	1240	1.7	2.1	28	1.8	12
18	12	1.8	980	2.1	2.1	1	2.4	15
19	13	1.8	1110	1.7	2.1	22	2.1	21
20	15	1.8	868	2.5	1.7	−32	2.2	−11
21	18	1.8	907	2.3	1.7	−26	2.1	−8
22	23	1.8	1130	1.7	1.7	−1	1.6	−4
23	25	1.8	950	2.3	1.7	−27	2.0	−14
24	26	1.8	1290	1.4	1.7	23	1.4	3
25	26	1.8	975	2.2	1.7	−22	1.9	−11
26	28	1.8	1170	1.5	1.6	2	1.5	−4
27	28	1.8	1200	1.5	1.6	3	1.4	−6
28	28	1.8	1100	1.8	1.6	−13	1.6	−13
29	29	1.8	1090	1.7	1.6	−7	1.6	−6

Abbreviations: MC, Monte Carlo; $CTDI_{vol}$, volume computed tomography dose index.

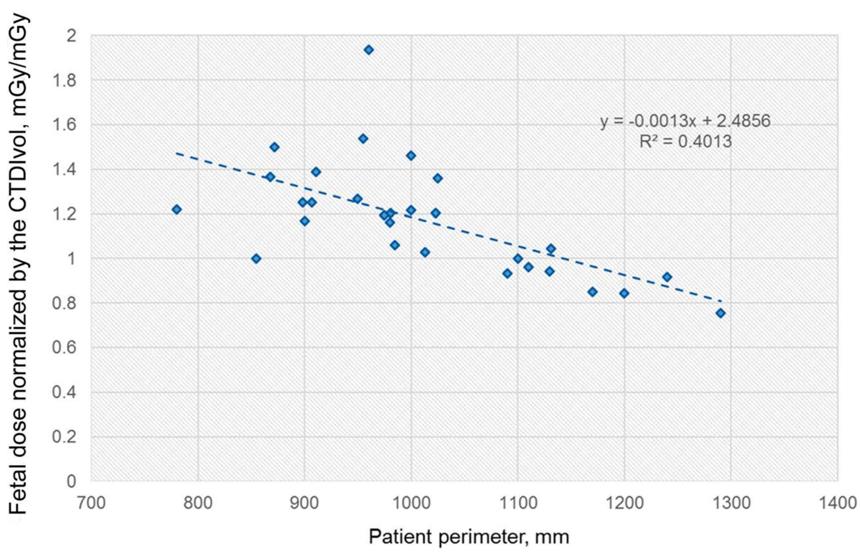

FIGURE 2. Scatterplot and regression analysis of the patient-specific fetal dose normalized by the $CTDI_{vol}$ as a function of maternal perimeter.

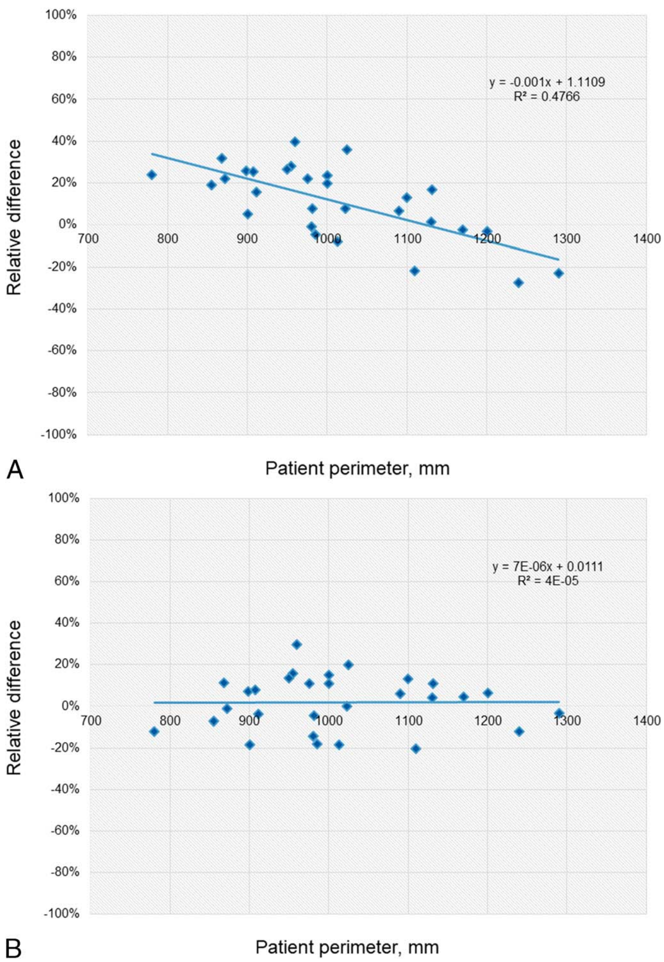

FIGURE 3. Scatterplot and regression analysis of the relative differences between the fetal dose provided by the computational algorithm and that calculated by patient-specific MC simulations as a function of maternal perimeter (A). After correction by the maternal perimeter the algorithm is more accurate, showing only a small relative error as compared with patient-specific MC simulations (B).

Web-Based Tool

We developed a noncommercial user-friendly tool (see www.fetaldose.org) for calculating fetal radiation doses based on the computational model described above (Fig. 4). The first input parameter required is the selection of the trimester (ie, first, second, or third) from the drop-down menu "gestational age." When the trimester is selected, an image of the corresponding phantom appears on the patient model display. Then the tube voltage must be selected from the drop-down menu. Based on the selection of trimester and tube voltage, the software defines the respective column in the table with $CTDI_{vol}$-normalized values (see Supplementary Table 1, http://links.lww.com/RLI/A537) obtained from respective MC simulations for further calculations.

After that, the start and end positions of the CT scan range must be adjusted using click-and-drag controllers. These positions are defined in millimeters assuming the lower position (the bottom of the feet) to be 0 mm and the top of the mothers head to be 1635 mm. Based on this information, the software defines the start and end of the column in Supplementary Table 1, http://links.lww.com/RLI/A537 for axial aggregation. All values between the start and end position are summed up. Finally, the user must type in the radiation output parameter $CTDI_{vol}$ of the CT examination on the panel. This value is used by the software tool to convert the $CTDI_{vol}$-normalized fetal dose to the final result. After clicking the results button, the fetal dose is calculated. In addition to the required input parameters, the user can optionally provide the maternal perimeter (in millimeters) to further improve the accuracy of the calculated fetal dose (see above). A further optional parameter is the patient ID. The entire dose report can be printed or saved in a PDF format for documentation in the patient's electronic records.

Importantly, fetal dose calculations can be performed with this tool for both, scans including the fetus within the scan-FoV and for scans not covering the uterus (ie, scatter radiation dose assessments).

DISCUSSION

Advertent or inadvertent irradiation of pregnant patients with CT requires estimation of the radiation dose received by the fetus, which—however—is difficult to accomplish in clinical routine. Earlier tools use simplified mathematical phantoms, are associated with considerable errors, are costly and require skilled staff to perform the calculations, or are restricted to fetal dose calculations during early gestation only.[15,26–28,30] Comparing with previous literature and available tools in this field, our computational algorithm and web-based tool provides the following advantages: (i) realistic pregnant patient geometry, (ii) ability to take patient-specific size into account, (iii) only few input parameters required enabling its use in daily clinical routine, (iv) high accuracy, and (v) fast calculations.

Angel et al[22] reported an average radiation dose to the fetus from abdominal CT of 10.8 mGy/100 mAs, and Damilakis et al[24] reported fetal doses from abdominal CT ranging between 13.5 and 31.6 mGy. Both studies showed correlations between fetal dose and maternal perimeter. Our study confirms these results by showing a median fetal dose of 2.7 mGy (interquartile range 10.6 mGy), along with a significant correlation between dose normalized by the $CTDI_{vol}$ and maternal perimeter. The lower fetal dose in our study as compared with the literature[22,24] is explained by the lower dose of our protocol ($CTDI_{vol}$ of 1.8 mGy in 51% of our patients).

The methods described above[22,24] are applicable for abdominal CT protocols with a single tube voltage (120 kV) only; however, recent approaches aim toward abdominal CT scanning with lower tube voltages.[36] In addition, these methods do not allow taking alternative scan lengths and body regions into account. In contrast, our approach allows for radiation dose assessments from any scanned body region, scan length, and CT protocol. The tool provides assessment of the fetal dose, with an average error of 11% compared with patient-specific MC simulations.

We could demonstrate that the dose values provided by our computational algorithm were more accurate with less variation in relative error than those from a widely available commercial dose monitoring software tool (Radimetrics Enterprise Platform, Bayer HealthCare). One of the potential reasons could be that this software takes patient

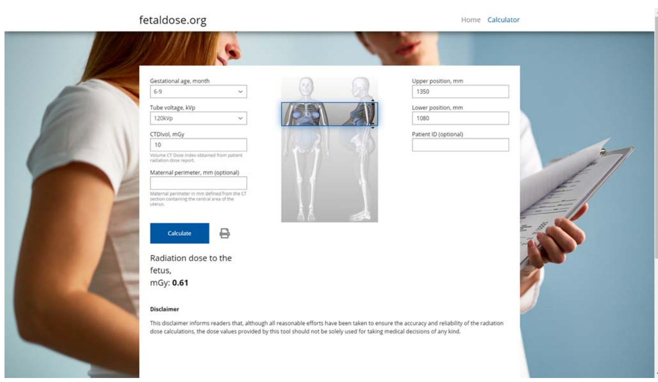

FIGURE 4. Graphical user interface of the web page for calculating fetal doses showing the example of a pregnant patient undergoing chest CT.

size into account by correcting the absorbed organ doses in the standard phantom by the water-equivalent diameter of the patient. However, this diameter is calculated as the average along the entire scan range,[37] which might lead to underestimation of abdominal diameter and, thus, wrong estimations of the fetal dose.

We developed a user-friendly web-based interface (www.fetaldose.org) being for free and requiring no registration and which allows for fast and accurate fetal dose calculations requiring the input of only a few parameters: gestational age and tube voltage and $CTDI_{vol}$ of the respective CT examination. Further optional parameters are the maternal perimeter, which serves for improved accuracy of the fetal dose calculations, and the patient ID, which can be used by the caregivers for the dose report. For being compatible with clinical routine, the webpage can be accessed via different web browsers, including Google Chrome, Mozilla Firefox, and Microsoft Internet Explorer. It can be further accessed via mobile devices using iOS and Android operating systems.

We have to acknowledge the following study limitations. First, the RPI phantoms used in this study represent 3 discrete gestational stages and no gestational ages in between. Second, the generic model of the CT scanner was validated for 2 systems from 2 vendors. Moreover, the shaping filter for our generic CT model was built based on the information provided by 1 vendor, which might lead to uncertainty in dose assessments for patients scanned with other CT scanners. In addition, our approach does not allow to take realistic TCM including the start angle and the trajectory into account, leading to potential inaccuracy of up to 25%.[38] However, we intentionally did not include TCM curves as required input parameter to our calculator because the tool was designed to be easy and applicable in clinical routine, while the shape of the real modulated tube current curve is usually not available to radiologists. Additional features, which may substantially vary from the assumptions used in generalized models, including the presence of arms or the exact position of the organs in the scan-FoV, might affect the accuracy of dose assessment. Third, since patient-specific fetal dose assessments by means of MC simulations require the fetus/uterus to be inside the scan-FoV, validation of our algorithm could be performed only for abdomen and abdomen-pelvis CT. To overcome this limitation, we compared the results of our tool with fetal dose values published by Kelaranta et al[10] for CT pulmonary angiography performed at different stages of pregnancy. The fetal doses provided by www.fetaldose.org showed good agreement with those published results (0.02 vs 0.03, 0.08 vs 0.08, and 0.18 vs 0.22 mGy for the first, second, and third trimester, respectively). Finally, the number of pregnant patients included in this study was relatively low.

We would like to underline that emphasis of this tool was given to a dynamic web-based dose assessment, user-friendly interface and a minimal set of input parameters available from CT dose reports. Although all reasonable efforts have been made to provide robust and accurate dose assessments, www.fetaldose.org should not be used as the sole measure for clinical decision making.

In conclusion, this article introduces a validated algorithm for accurate assessment of radiation dose absorbed by the fetus from CT of pregnant patients from any body region and provides a freely available, user-friendly web interface enabling fast fetal dose calculations.

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